DOI: http://doi.org/10.25728/cs.2022.5.1

DESIGNING AN ADAPTIVE STABILIZING SYSTEM FOR AN UNMANNED AERIAL VEHICLE

N.A. Pervushina[1] and A.D. Frolova[2]

Zababakhin All-Russian Research Institute of Technical Physics (VNIITF),
Russian Federal Nuclear Center, Snezhinsk, Russia

[1]✉ p-n-a100678@yandex.ru, [2]✉ antonina.garishina@yandex.ru

Abstract. This paper presents a mathematical model of an efficient adaptive stabilizing system in the pitch channel of an unmanned aerial vehicle. The model is described by a functional block diagram and is based on a correction method proposed for onboard computers. Some structural modifications are suggested for the correction loop to improve the performance of the stabilizing system of the nonlinear dynamic item under control mode switching. The operation of the stabilizing system is simulated with the tuned parameters of the correction loop under fixed gains of the main loop. The new structure of the correction loop in the stabilizing system demonstrates high efficiency in the operation modes of the vehicle. Due to the proposed design procedure, the stabilizing system with the new structure of the correction loop is constructed several times faster compared with the classical method of fixed factors.

Keywords: unmanned aerial vehicle, pitch channel, stabilizing system, mathematical modeling, design, the efficiency of a stabilizing system.

INTRODUCTION

The performance and operability of a stabilizing system (SS) of an unmanned aerial vehicle (UAV) in a domain corresponding to its admissible application conditions are determined by the aerodynamic properties of the guided item and the chosen structure of the control signal. The traditional solution of the SS design problem with constructing a linearized model of the UAV for each flight mode and approximating the resulting coefficients depending on the dynamic head by the method of fixed factors ensures system operation in the entire range of flight modes [1, 2] but requires computing cost. Therefore, finding the most efficient ways of solving this problem is topical. The efficiency of a system or process is usually understood as the ratio of the result achieved and the resources used.

This paper considers airplane-type guided UAVs with the normal aerodynamic scheme, a large elongation wing, and differential rudders. The object of study is the longitudinal control channel (pitch channel) in the UAV stabilizing system. The goal of study is to develop a mathematical model of an effective adaptive stabilizing system in the pitch channel. The effectiveness of the SS will be understood as system operation in switching modes with the highest possible performance in the entire range of flight modes with the minimum computing cost of the design procedure. A stabilizing system with these properties will be called efficient.

There are ways to improve the performance of the SS by increasing its speed. A term corresponding to some additional impact on the controls is introduced in the control signal structure of the pitch channel of the UAV. In [3–7], the control signal in the pitch channel was formed by an overload discrepancy, an integral of discrepancy, a signal proportional to the pitching rate (damper), i.e., an analog of a proportional-integral-differential (PID) controller, and an additional balancing signal or a signal similar to the pilot force applied to the stick. As shown in [9], when the aerial vehicle reaches a given altitude, the automatic thrust force control is implemented by a similar law. In [10], the control signal applied to the elevators was also formed with an additional term proportional to the angle of attack. A similar technique was used to improve the performance of the overload stabilization loop in the coefficient adaptation algorithm [11]. These examples of control signals in the pitch channel allow improving the quality of transients (increasing the speed). However, for the SS to operate in the entire range of admissible modes, we still need a specific set of system gains for each nominal point of this range.

Modern UAVs are designed to operate in various, particularly extreme, flight modes. The most difficult and dangerous modes are the critical ones in terms of the angle of attack. If the critical angles of attack are exceeded, the control efficiency of the UAV decreases. The paper [12] proposed a two-loop stabilizing system in the pitch channel where the auxiliary loop limits the angle of attack through an algebraic selector: it changes the system structure in accordance with the channel switching logic. This approach yields a well-damped system, but significantly restricting the angle of attack increases the transient time.

A mathematically justified method for designing linear systems with the minimum settling time was presented in [13]. The time-optimal solution was obtained using the theory of optimal controllers.

Fuzzy controllers are often employed to stabilize dynamic plants in modern control systems. This class of controllers has low sensitivity to changes in the plant's parameters and is characterized by high speed and accurate positioning [14, 15]. According to computer simulations [16], fuzzy controllers used for stabilizing the UAV in the pitch channel demonstrate high speed. However, such controllers are difficult to describe due to a rule base developed for the input parameters.

Currently, there are many examples of fuzzy controllers improving the performance of control systems [17–21]. Fuzzy controllers do increase the speed of systems, but they require additional tuning depending on the operation mode and under control mode switching.

In this paper, we construct a mathematical model of an efficient SS based on the approach described in the monograph [2]. This approach requires no parameter changing and involves the method of fixed factors. The authors [2] proposed a fast reduction of the control error using an additional signal of an appropriate sign when the stabilization error exceeds a certain threshold.

The results presented below were obtained by computer modeling. The flight of an aerial vehicle in the Earth's atmosphere is described by a system of nonlinear ordinary differential equations with coefficients that depend on free stream parameters.

The following problems are sequentially solved in this paper:

– Mathematical models of the guided item and SS are developed.

– The mathematical model of the SS is designed, and the correction loop parameters are tuned.

– Some structural modifications are suggested for the correction loop to improve the performance of the SS. The operation of the SS with the new correction loop is tested.

1. PROBLEM STATEMENT

To develop a mathematical model of an efficient adaptive stabilizing system, we choose the classical structure of the SS in the pitch channel [19] with the control signal

$$\sigma_{\text{elev}} = K_i \int_{t_0}^{t} \Delta n_y dt + K_n \Delta n_y - K_{\omega_z} \omega_z \tag{1}$$

and the following notations: $\Delta n_y = n_{y\,\text{giv}} - n_y$ is the discrepancy value, where $n_{y\,\text{giv}}$ is a given value of the normal overload and n_y is the SS output; σ_{elev} is the elevator control signal, in deg; K_i, K_n, and $K\omega_z$ are known gains of appropriate dimension; finally, ω_z is the pitching rate, in deg/s.

We form the additional control signal σ_{add} using a functional analog of the pulse correction scheme that can be implemented in digital onboard systems [2]. Consider a scheme consisting of an integrator and an aperiodic link that are connected in parallel with the main stabilization loop when the stabilization error exceeds a given threshold. Connecting the scheme to the stabilization error signal Δn_y and the pitching rate signal ω_z reduces the overshoot and the rate of oscillation due to a small error threshold when increasing the system speed.

Figure 1 shows the block diagram of the pitch channel stabilizing system with the control signal (1) when connecting the correction loop as recommended in [2].

Figure 1 has the following notations: σ_{elev} is the equivalent elevator control signal, in deg; δ_{elev} is the equivalent elevator angle, in deg; δ_{add} is the additional control signal during the correction, in deg; σ_{thres} is the threshold control signal, in deg; K_n, K_ω, K_1, K_2, and K_3 are the appropriate-dimension gains of the auxiliary loop of the stabilizing system; T is the time constant of the aperiodic link in the correction loop, in s; sign(σ_{thres}) is the sign function [20]; finally, p is the Laplace transform variable.

The guided item is described by a nonlinear mathematical model in the aircraft-linked coordinate system [1, 19]:

$$\begin{cases} \dfrac{d\omega_z}{dt} = \dfrac{m_z qSL}{I_{zz}} \times \dfrac{180}{\pi}, \\ \dfrac{d\alpha}{dt} = \left(\dfrac{g\cos\vartheta}{V} - \dfrac{c_y qS}{mV} \right) \dfrac{180}{\pi} + \omega_z, \\ \dfrac{d\vartheta}{dt} = \omega_z, \end{cases} \quad (2)$$

where α is the angle of attack, in deg; ϑ is the pitch angle, in deg; $m_z = m_z(\mathrm{M}, \alpha, \delta_{\mathrm{elev}}, ...)$ is the aerodynamical coefficient of the pitching moment, which nonlinearly depends on the free stream parameters, the elevator angle, etc., a dimensionless quantity; $c_y = c_y(\mathrm{M}, \alpha, \delta_{\mathrm{elev}}, ...)$ is the aerodynamical lifting force coefficient, which nonlinearly depends on the free stream parameters, the elevator angle, etc., a dimensionless quantity; M is the Mach number; q is the dynamic head, in Pa; S is the midship area, in m^2; L is the characteristic linear dimension of the aerial vehicle, in m; m is the aerial vehicle mass, in kg; V is the airspeed of the aerial vehicle, in m/s; finally, g = 9.80665 m/s^2 is free fall acceleration.

In this problem, the actuator of the elevator has the linear mathematical model

$$T_{\mathrm{A}} \frac{d\delta_{\mathrm{elev}}}{dt} + \delta_{\mathrm{elev}} = \sigma_{\mathrm{elev}}, \quad (3)$$

where T_{A} = 0.025 s is the time constant of the actuator.

For example, consider five nominal points of the aerial vehicle trajectories (Table 1).

Table 1

Nominal points of trajectories

Parameters, units of measurement	Nominal points				
	1	2	3	4	5
q, kPa	5.5	10.5	20	30.5	44
V, m/s	100	160	200	250	270

The performance requirements for the stabilizing system in the entire range of nominal points of the aerial vehicle trajectories are as follows:

- The time t_{set} to execute a given control step excitation (5% of the steady-state value) must be about 1.5 s.
- The overshoot σ in the transients at the SS output must be minimum, not exceeding 30%.

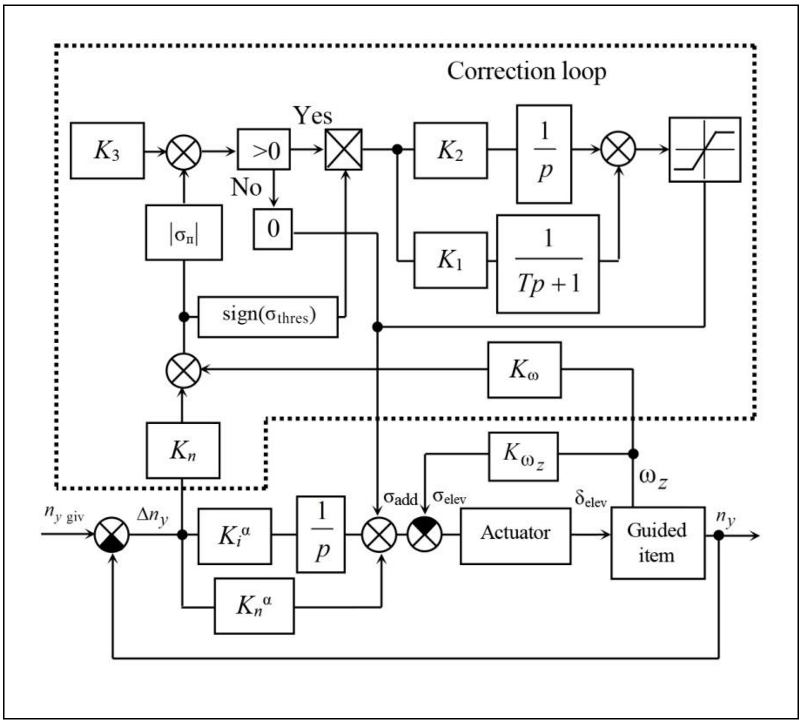

Fig. 1. The block diagram of the SS in the pitch channel with the correction loop.

- The maximum value of the control signal σ_{elev} in the SS must not exceed ±20°.
- At the design stage, the gain margin L_{mar} must be at least 10 dB.
- At the design stage, the phase margin φ_{mar} must be at least 30°.

2. DESIGNING THE MAIN LOOP OF THE STABILIZING SYSTEM

The system of differential equations (2) is linearized in the neighborhood of each nominal point; see Table 1. For linearization, we simplify the aerodynamical coefficients model:

$$c_y = c_{y_0} + c_y^{\alpha}\alpha + c_y^{\delta_{\mathrm{elev}}}\delta_{\mathrm{elev}},$$

$$m_z = m_z^{\alpha}\alpha + m_z^{\delta_{\mathrm{elev}}}\delta_{\mathrm{elev}}, \quad (4)$$

with the following notations: c_{y_0} is the aerodynamical coefficient c_y for α = 0 and δ_{elev} = 0; c_y^{α} is the derivative of the coefficient c_y with respect to the angle of attack, in deg^{-1}; $c_y^{\delta}{}_{\mathrm{elev}}$ is the derivative of the coefficient c_y with respect to the elevator angle, in deg^{-1}; m_z^{α} is the derivative of the coefficient m_z with respect to the angle of attack, in deg^{-1}; finally, $m_z^{\delta}{}_{\mathrm{elev}}$ is the derivative of the coefficient m_z with respect to the elevator angle, in deg^{-1}.

The relationship between the overload and the angle of attack [21] is described by

$$n_y = \left(c_y^{\alpha} Sq / mg\right)\alpha. \qquad (5)$$

For $\triangle\vartheta \approx 0$, the linearized system of differential equations has the form

$$\begin{cases} \dfrac{d\omega_z}{dt} = m_z^{\alpha}\dfrac{qSL\times180}{I_z\pi}\alpha + m_z^{\delta_{\text{elev}}}\dfrac{qSL\times180}{I_z\pi}\delta_{\text{elev}}, \\ \dfrac{d\alpha}{dt} = -c_y^{\alpha}\dfrac{qS\times180}{mV\pi}\alpha - c_y^{\delta_{\text{elev}}}\dfrac{qS\times180}{mV\pi}\delta_{\text{elev}} + \omega_z. \end{cases} \qquad (6)$$

Under the above requirements, we designed the main loop of the SS in the pitch channel (Fig. 1) using the method of amplitude-log responses [20] for the guided item (6). The resulting gains K_i, K_n, and $K\omega_z$ of the main loop as well as the values of the performance indicators and stability margins are combined in Table 2.

The transients in the main loop of the SS with the linearized guided item (4) are shown in Fig. 2. In the graphs of Figs. 2 and 3, the results for point 1 are indicated by a black bold line; for point 2, by a black thin line; for point 3, by a black dashed line; for point 4, by a gray bold line; for point 5, by a gray dashed line.

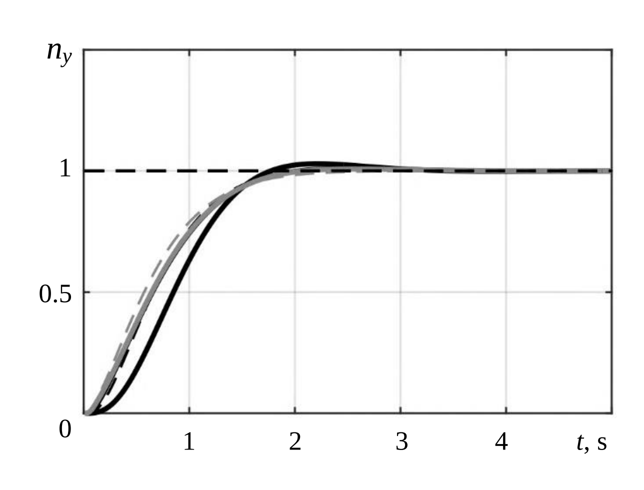

Fig. 2. Transients in the main loop of the SS in the pitch channel.

Table 2

The main loop of the SS

Nominal points	SS gains			Performance indicators		Stability margins	
	K_i	K_n	$K\omega_z$	t_{set}, s	σ, %	L_{mar}, dB	φ_{mar}, °
1	– 10.86	– 0.098	– 0.239	1.50	1.4	14	66
2	– 6.488	– 0.889	– 0.290	1.55	1.0	31	71
3	– 2.796	– 0.051	– 0.175	1.50	0.1	21	71
4	– 2.289	– 0.176	– 0.259	1.55	0.5	36	73
5	– 1.702	– 0.092	– 0.178	1.48	0.1	35	74

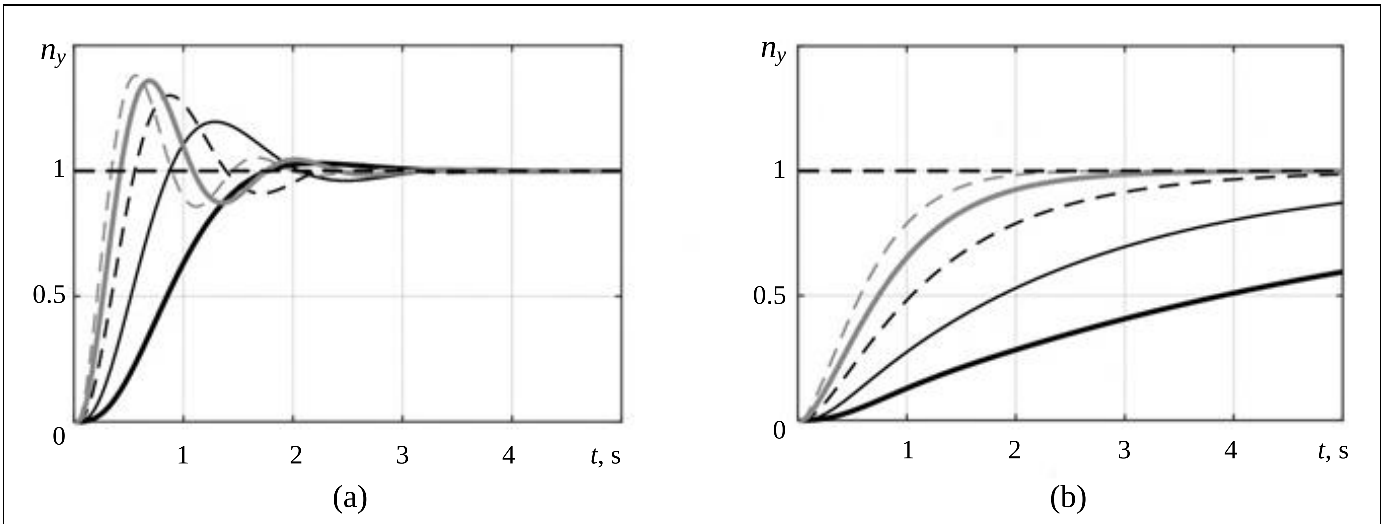

Fig. 3. Transients in the main loop of the SS in the pitch channel: (a) the gains K_i = – 10.86, K_n = – 0.098, and $K\omega_z$ = – 0.239 (point 1) and (b) the gains K_i = – 1.702, K_n = – 0.092, and $K\omega_z$ = – 0.178 (point 5).

This design procedure of the main loop of the SS in the pitch channel at each nominal point of the UAV trajectory illustrates the method of fixed factors. Further, the resulting coefficients are traditionally approximated depending on the dynamic head: $K_i(q)$, $K_n(q)$, $K\omega_z(q)$. The result is an adaptive SS.

This design procedure is computationally intensive due to considering each nominal point. Indeed, the SS gains vary significantly; see Table 2. For instance, the coefficient K_i = – 10.86 for point 1 and K_i = – 1.702 for point 5 differ almost tenfold.

As an example, Figs. 3a and 3b show the simulated operation of the SS with the linearized guided item (3) and the gains corresponding to the extreme points (1 or 5).

At nominal points with a small dynamic head (point 1), a large control action is required for stabilization. In other modes, however, this control action turns out excessive (Fig. 3a). For instance, when simulating the operation of the SS at nominal point 5, the overshoot reaches 40%, which is unacceptable. At nominal points with a high dynamic head (point 5), such a control action becomes unnecessary. In this case, when simulating the operation of the SS at nominal point 1, the transient time increases manifold; therefore, the control action is insufficient (Fig. 3b).

We use a correction loop (Fig. 1) to increase the efficiency of the SS (stabilize the pitch angle in the entire range of nominal points using only one set of gains).

3. TUNING THE CORRECTION LOOP

The recommendations provided in [2], semi-empirical in nature, can underlie a tuning procedure for the parameters of the correction loop (the auxiliary loop) depending on the dynamic properties of the UAV under consideration. According to these recommendations, the time constant T of the aperiodic link in the correction loop (Fig. 1) is related to the coefficient K_2 at the integrator. More precisely, the smaller this constant is, the greater value the coefficient will take. A larger value of the coefficient increases the speed of discrepancy processing but can quickly bring the scheme to saturation, so the choice of the time constant T is determined by the performance requirements for a particular system. In an initial approximation, the time constant T should be taken 10–15 times greater than the time constant T_A (3) of the actuator. We restrict the control signal of the correction loop to ±10° (50% of the maximum value of the control signal according to the SS requirements). The other parameters of the correction loop are selected depending on the properties of the guided item and actuator and the operation modes of the SS.

3.1. Tuning under the Single Step Excitation

The parameters of the auxiliary control loop were tuned under a typical single step excitation of the form

$$n_{y\text{ giv}} = 1(t) = \begin{cases} 0 \text{ for } t < 0, \\ 1 \text{ for } t \geq 0. \end{cases} \quad (7)$$

Let the main loop of the SS be designed for the nominal point with the smallest dynamic head (point 1). In this case, the auxiliary loop is intended to reduce the control action: the other nominal points have a greater value of the dynamic head, and this control action will be excessive for them (Fig. 3a).

In accordance with the above recommendations, the correction loop was configured to work the influence (7). The values of the loop parameters after tuning are shown in Table 3.

Table 3

Correction loop parameters

Parameters	T	K_1	K_2	K_3	K_n	K_ω
Values	0.25	0.1	10	0.5	0.1	– 0.25

In the scheme of Fig. 1, the signal σ_{add} enters the main loop of the SS with the minus sign. The simulated operation of the SS with the additional loop is shown in Fig. 4 (bold line).

According to the simulation results, the gains of the main loop obtained for point 1 work with the correction loop in the system with the guided item's mathematical model for point 5 and the input (5).

Now we test the SS in the case when the input amplitude differs from 1. The simulation results are presented Figs. 5a and 5b. The graphs indicate that the correction result depends on the input value of the SS. However, this feature is not stipulated by the correction loop scheme selected in the paper (Fig. 1).

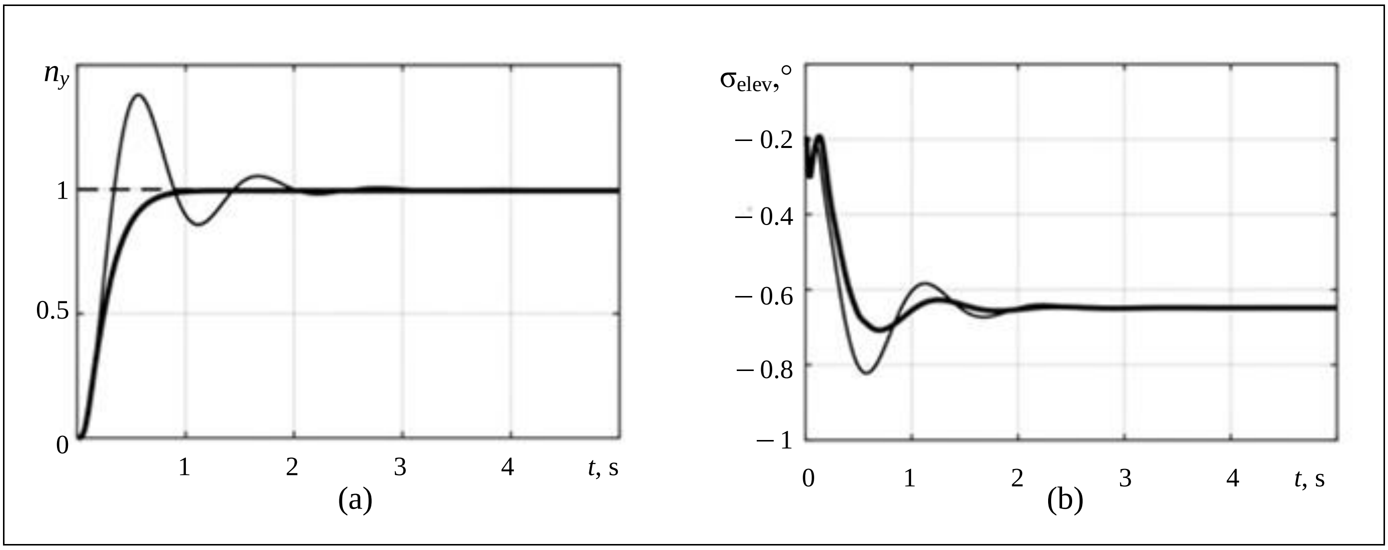

Fig. 4. Parameters of the SS in the pitch channel before and after correction: (a) n_y and (b) σ_{elev}.

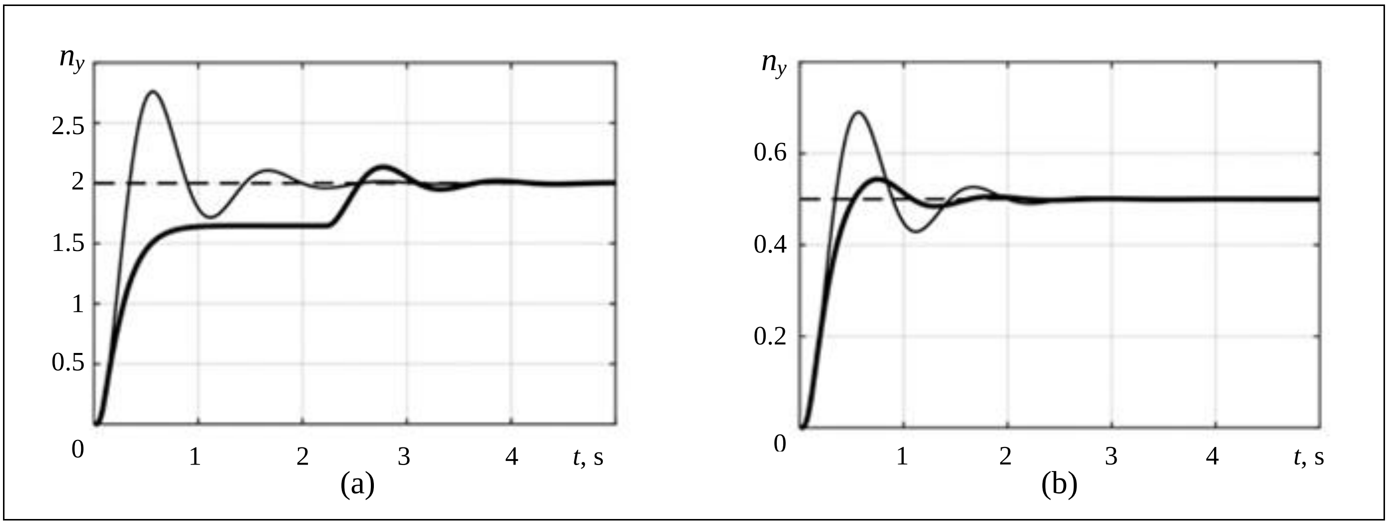

Fig. 5. Output processes of the SS in the pitch channel: (a) $n_{y\ giv} = 2\cdot 1(t)$ and (b) $n_{y\ giv} = 0.5\cdot 1(t)$.

3.2. Structural Modifications in the Correction Loop

In view of the aforesaid, we suggest considering $n_{y\ giv}$ as an input signal of the correction loop of the SS. This structural modification of the auxiliary loop is shown in Fig. 6.

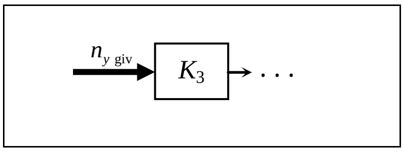

Fig. 6. The suggested modification in the correction loop scheme.

3.3. Simulation of the Stabilizing System at Each Nominal Point

Let us simulate the operation of the modified SS (Fig. 6) at the nominal points (Table 1). The simulation results are demonstrated in Fig. 7 except for point 5 (loop tuning; see Fig. 4).

According to these graphs, the additional control signal σ_{add} worsens the transients when passing from one nominal point to another with a decrease in the dynamic head (i.e., when the main loop of the SS approaches its initial settings). In other words, the SS loop with the gains obtained at the design stage (for

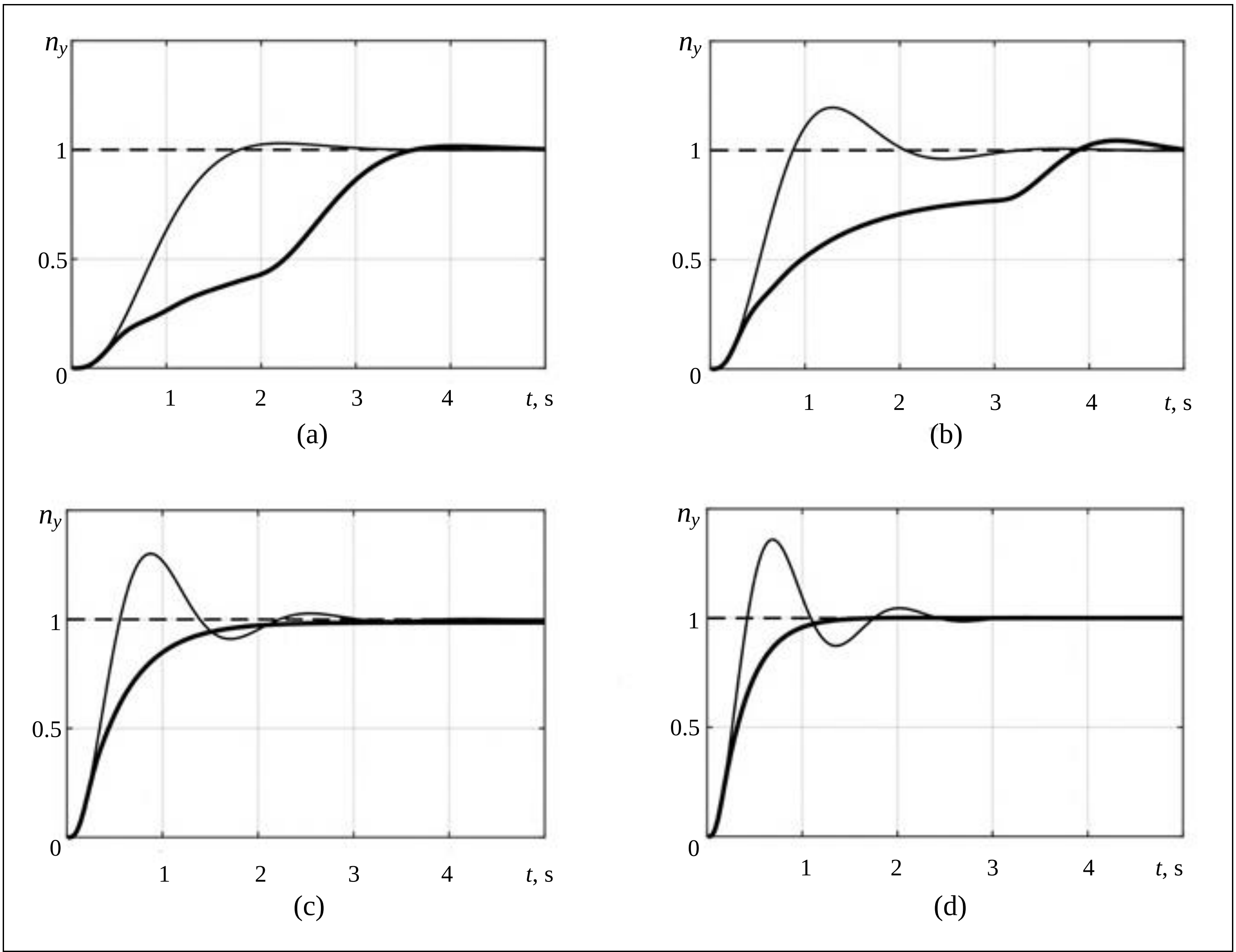

Fig. 7. Output processes of the modified SS in the pitch channel: (a) point 1 (q = 5.5 kPa), (b) point 2 (q = 10.5 kPa), (c) point 3 (q = 20 kPa), and (d) point 4 (q = 30.5 kPa).

point 1) needs no additional correction. For the other points (2, 3, and 4), it is necessary to gradually increase the correction effect and, hence, the signal σ_{add}.

3.4 Tuning the Control Signal σ_{add}

To regulate the degree of correction, we suggest a dimensionless coefficient K that depends on the dynamic head q as follows: if q = 44 kPa (max), then K = 1; if q = 5.5 kPa (min), then K = 0. Let the coefficient K change linearly between the nodal points. The linear approximation of K is given by

$$K(q) = 0.026q - 0.143, \quad (8)$$

where q is the dynamic head, in kPa.

Considering (8), the signal σ_{add} takes the form

$$\sigma_{add} = K(q)\,\sigma^{*}_{add}, \quad (9)$$

where σ^*_{add} is the control signal of the correction loop before the tuning procedure (8).

Figure 8 shows the simulation results of the SS with the control signal (9) for points 1 and 5. These graphs are the counterparts of the ones presented in Fig. 7.

3.5. Simulation of the Stabilizing System with the Nonlinear Guided Item

Next, we simulate the operation of the SS under the following conditions:

1) The guided item in the pitch channel is described by the system of nonlinear differential equations (2).

2) The aerodynamical coefficients model is:

2.1) linear (4),

2.2) nonlinear.

3) The control signal in the main loop has the structure (1).

4) The control signal in the auxiliary loop has the structure shown in Fig. 1.

5) The actuator model is described by the differential equation (3), written in difference form as

$$\delta_{\text{elev}_i} = a\sigma_{\text{elev}_{i-1}} + b\delta_{\text{elev}_{i-1}},$$

where $a = h / T_{\text{A}}$ and $b = e^{-h/T_{\text{A}}}$.

6) The relation between the overload and the angle of attack is described by formula (5).

7) The system of equations (2) is integrated using the fourth-order Runge–Kutta method with an integration step h, a conventional approach in the numerical modeling of aircraft flight dynamics.

Figure 9 shows the simulation results under conditions 1)–7) for the linear aerodynamical coefficients model with h = 0.01 s.

In Fig. 9, the results for point 1 are indicated by a black bold line; for point 2, by a black thin line; for point 3, by a black dotted line; for point 4, by a gray bold line; for point 5, by a gray thin line.

The values of the integral performance criteria of the processes in Fig. 9 are combined for comparison in Table 4. The values of the integrated square error (ISE) and the integrated weighted absolute error (IWAE) decreased significantly during the execution of the single step excitation. For instance, for the extreme nominal point 5, the IWAE value decreased by 4.5 times.

The performance of transients in the SS was also assessed by the settling time t_{set} and the overshoot σ. The estimated values of these indicators are given in Table 5.

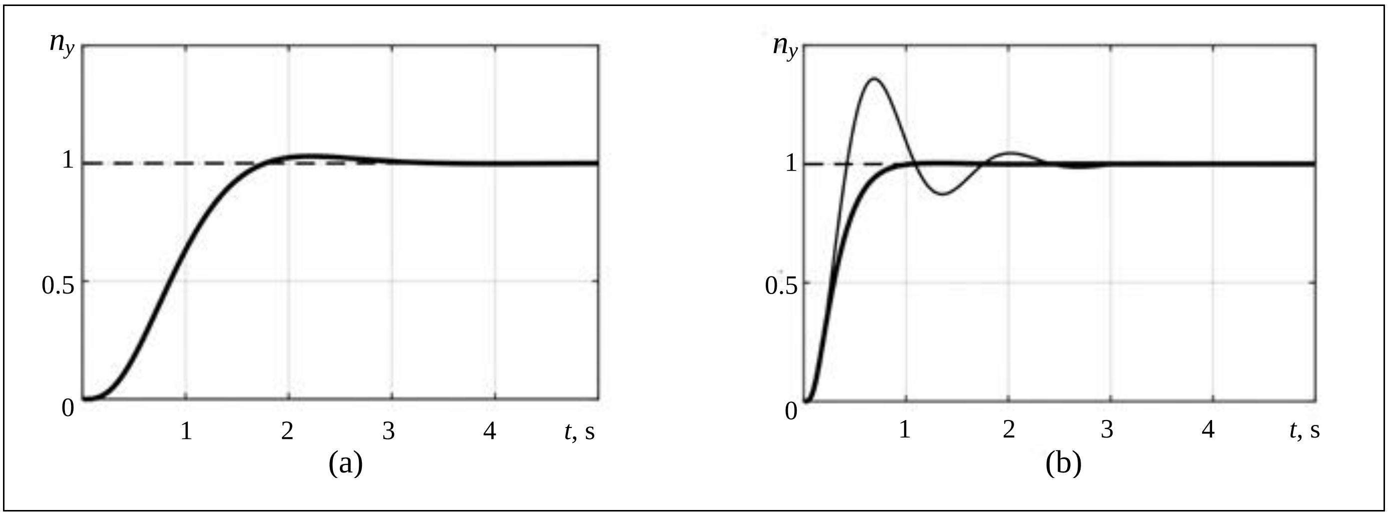

Fig. 8. Output processes of the SS with the tuned control signal σ_{add}: (a) point 1 (q = 5.5 kPa) and (b) point 4 (q = 30.5 kPa).

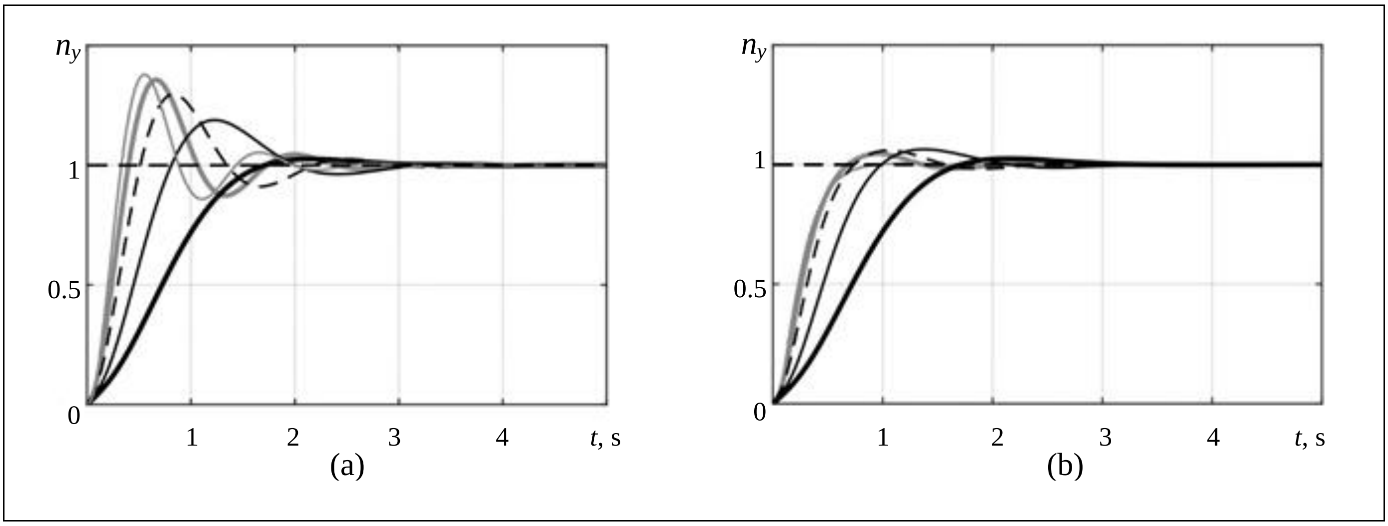

Fig. 9. Output processes of the SS: (a) before correction and (b) after correction.

Table 4

Integral performance criteria

Nominal point	Without correction		With correction	
	$\text{ISE} = \int_0^T \left(n_{y\text{ giv}} - n_y\right)^2 dt$	$\text{IWAE} = \int_0^T t\left\lvert n_{y\text{ giv}} - n_y\right\rvert dt$	ISE	IWAE
1	0.479	0.409	0.479	0.409
2	0.329	0.414	0.312	0.236
3	0.248	0.338	0.213	0.124
4	0.218	0.289	0.178	0.082
5	0.191	0.220	0.160	0.047

Table 5

Performance indicators of transients

Nominal point	Indicators			
	Without correction		With correction	
	t_{set}, s	σ, %	t_{set}, s	σ, %
1	2.1	6	2.1	6
2	2.4	24	1.6	9
3	1.9	34	1.2	7
4	2	40	0.9	5
5	1.7	42	0.6	0

For instance, for nominal point 5, the time t_{set} decreased by 3 times and the overshoot σ decreased by 42% during the execution of the single step excitation.

Figure 10 presents the simulation results for the nonlinear aerodynamical coefficients model. The range of the dynamic head q on the simulated trajectory was from 25 to 6.5 kPa. The gains of the control signal (1) in the main loop were fixed and corresponded to nominal point 1: $K_i = -10.86$, $K_n = -0.098$, and $K\omega_z = -0.239$. The gains of the auxiliary loop were taken from Table 3.

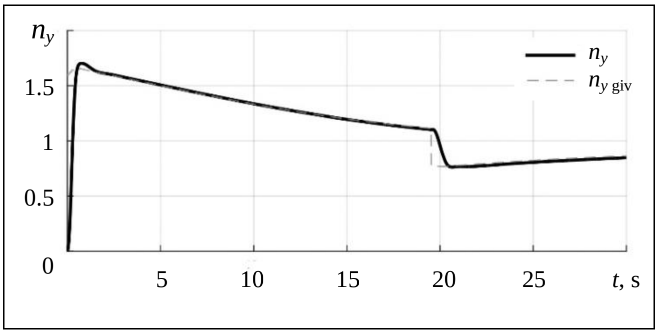

Fig. 10. The output process of the SS with the correction loop for the nonlinear aerodynamical coefficients model.

For comparison, Fig. 11 shows the simulated operation of the SS without the correction loop with the gains calculated depending on the dynamic head q according to Tables 1 and 2. Figure 12 demonstrates the deviations of the parameter n_y from the given values $n_{y\text{ giv}}$ for the two types of stabilizing systems.

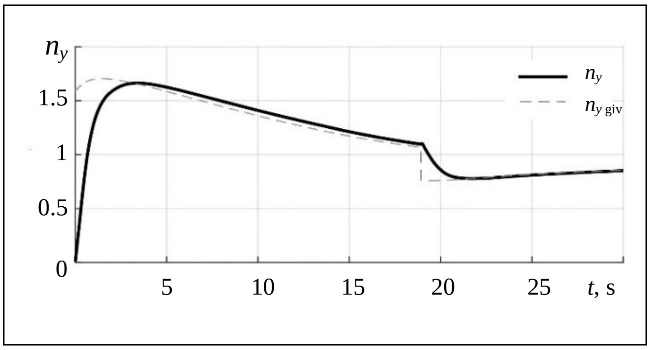

Fig. 11. The output process of the SS without the correction loop for the nonlinear aerodynamical coefficients model.

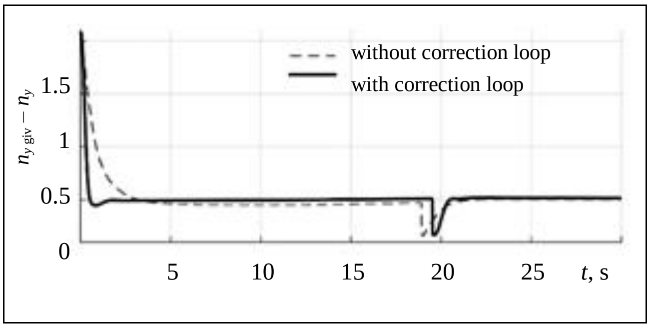

Fig. 12. The deviations of the parameter n_y from the given values $n_{y\text{ giv}}$ for the nonlinear aerodynamical coefficients model.

As follows from Fig. 12, the developed adaptive stabilizing system rapidly reduced the error. These results indicate the efficiency of the developed SS, the correct design procedure of the main loop, and the correct parametric tuning of the auxiliary loop. The proposed procedure works for the angles of attack within the range of ±24°. The absolute value 24° of the angle of attack is the limit for the UAVs under consideration.

Figure 13 presents the new block diagram of the pitch channel correction scheme based on the refinements and modifications suggested in this paper (shown in bold).

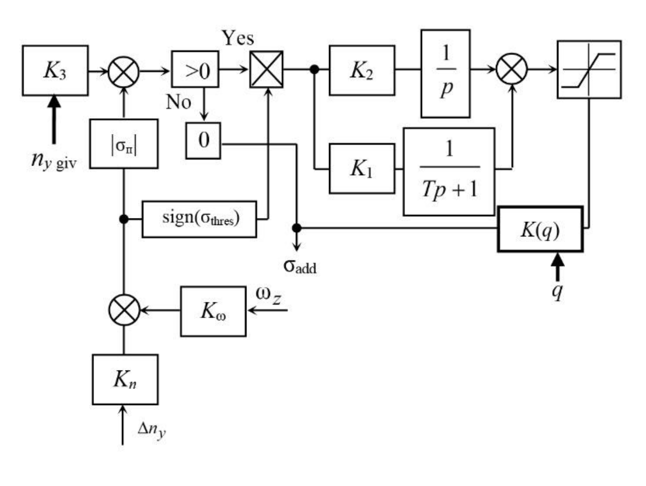

Fig. 13: The block diagram of the correction loop of the SS in the pitch channel.

CONCLUSIONS

This paper has presented a mathematical model of an efficient adaptive stabilizing system (SS) in the pitch channel of an unmanned aerial vehicle (UAV). The model is based on the correction method proposed for onboard computers.

The linearized mathematical model of the UAV has been simulated under different single step excitations. According to the simulation results, the performance of the SS worsens if the amplitude of the input excitation differs from the one used for tuning the correction loop. Therefore, the following structural modifications have been proposed for the auxiliary loop:

– treating a given excitation as an input signal,

– introducing a coefficient that depends on the dynamic head to regulate the degree of correction.

Computer simulations have been carried out with integration by the fourth-order Runge–Kutta method, and the values of integral performance criteria and performance indicators have been calculated. Based on these results, the stabilizing system with the new correction loop demonstrates a good quality of stabilization: no overshoot and high settling times of up to 0.6 s.

The mathematical model of the SS has been implemented in the program code. According to the simulation results, due to the proposed design procedure, the stabilizing system with the new structure of the correction loop is constructed several times faster compared with the classical method of fixed factors: the classical method is applied only for one nominal point (with the minimum dynamic head) from the set of admissible flight modes of the UAV. The constant coefficients of the correction loop are then tuned to ensure the operation of the SS in the entire range of flight modes (up to the maximum dynamic head), and the tuning procedure requires insignificant time compared with the main loop design procedure.

The design approach proposed above is recommended for developing digital adaptive stabilizing systems in the pitch channel of unmanned aerial vehicles to improve the quality of stabilization in a set of their operation modes while reducing the associated computing cost.

REFERENCES

1. Lebedev, A.A. and Karabanov, V.A., *Dinamika sistem upravleniya bespilotnymi letatel'nymi apparatami* (Dynamics of Control Systems for Unmanned Aerial Vehicles), Moscow: Mashinostroenie, 1965. (In Russian.)
2. Obnosov, B.V., Voronov, E.M., Mikrin, E.A., et al., *Stabilizatsiya, navedenie, gruppovoe upravlenie i sistemnoe modelirovanie bespilotnykh letatel'nykh apparatov. Sovremennye podkhody i metody* (Stabilization, Guidance, Group Control, and System Simulation of Unmanned Aerial Vehicles. Modern Approaches and Methods), Voronov, E.M., Mikrin, E.A., and Obnosov, V.M., Eds., Moscow: Bauman Moscow State Technical University, 2018. (In Russian.)
3. Onuora, A.E., Mbaocha, C.C., Eze, P.C., and Uchegbu, V.C., Unnamed Aerial Vehicle Pitch Optimization for Fast Response of Elevator Control System, *International Journal of Scientific Engineering and Science*, 2018, vol. 2, pp. 16–18.
4. Rodalski, T., Nowak, D., Walek, L., and Rzonca, D., Control System for Aircraft Take-off and Landing Based on Modified PID Controllers, *MATEC Web of Conferences*, 2019, vol. 252, art. no. 06008. DOI: https://doi.org/10.1051/matecconf/201925206008.
5. Sakharchuk, D.A., Sivashko, A.B., Kruglikov, S.V., et al., Directions of Creation and Development of Pilotless Aviation Complexes, *Science Intensive Technologies*, 2014, vol. 15, no. 5, pp. 22–26. (In Russian.)
6. Zhivov, Yu.G. and Poedinok, A.M., Adaptive Control System for Aircraft Longitudinal Motion, *TsAGI Science Journal*, 2012, vol. 43, no. 5, pp. 683–695.
7. Vassilyev, S.N., *Problemy upravleniya slozhnymi dinamicheskimi ob'ektami aviatsionnoi i kosmicheskoi tekhniki* (Control Problems for Complex Dynamic Aerospace Objects), Moscow: Mashinostroenie, 2015. (In Russian.)
8. Grebenkin, V.A., Developing Autoflare Algorithms for Landing with Interceptor Control, *Trudy MIEA. Navigats. Upravlen. Letat. Appar.*, 2013, no. 6, pp. 2–17. (In Russian.)
9. Kulikov, L.I., Synthesis of a Flight Control Algorithm for an Unmanned Parachute-Type Aerial Vehicle in the Barraging Mode at a Given Altitude, *Trudy 9-oi Nauchno-prakticheskoi konferentsii "Perspektivnye sistemy i zadachi upravleniya" i 4-oi molodezhnoi shkoly-seminara "Upravlenie i obrabotka informatsii v tekhnicheskikh sistemakh"* (Proceedings of the 9th Scientific and Practical Conference "Promising Systems and Problems of Control") and the 4th Youth School–Seminar "Control and Information Processing in Technical Systems"), Taganrog, 2014, pp. 226–227. (In Russian.)
10. Popova, I.V., Zemskov, A.V., Lestev, A.M., and Pestova, K.S., Control Algorithms for Gliding Unmanned Aerial Vehicles of

the Air-Surface Class, *Trudy 12-go Vserossiiskogo soveshchaniya po problemam upravleniya* (Proceedings of the 12th All-Russian Meeting on Control Problems), Moscow, Trapeznikov Institute of Control Sciences, 2014, pp. 3681–3689. (In Russian.)
11. Bystrov, D.A., Development and Research of Adaptation and Stabilization Algorithms in the System of an Aircraft, *Modern Science: Actual Problems of Theory and Practice. Natural and Technical Sciences*, 2014, no. 5/6, pp. 3–10. (In Russian.)
12. Abdullina, E.Yu. and Efanov, V.N., Synthesis of Pitch Angle Control System with Angle of Attack Limiting Channel, *Russian Aeronautics*, 2020, vol. 63, pp. 25–32.
13. Lovchakov, V.I., Synthesis of Linear Control Systems with Maximum Speed and Given Overshoot, *Mekhatronika, Avtomatizatsiya, Upravlenie*, 2020, vol. 21, no. 9, pp. 499–510. (In Russian.)
14. Piegat, A., *Fuzzy Modeling and Control*, Heidelberg: Physica-Verlag, 2001.
15. Vasil'ev, V.I. and Il'yasov, B.G., *Intellektual'nye sistemy upravleniya. Teoriya i praktika* (Intelligent Control Systems: Theory and Practice), Moscow: Radiotekhnika, 2009. (In Russian.)
16. Pervushina, N.A. and Khakimova, A.N., Development of Mathematical Models of Fuzzy Controllers Set by Genetic Algorithm to Stabilize Dynamic Object, *Control Sciences*, 2020, no. 4, pp. 3–14. (In Russian.)
17. Burakov, M.V. and Yakovets, O.B., Fuzzy Logic Control over a Power Gyroscopic System, *Journal of Instrument Engineering*, 2015, vol. 58, no. 10, pp. 804–808 (In Russian.)
18. Lysenko, L.N., Kyong, N.D., and Chyong, F.V., Motion Modeling for a Remotely Piloted Aerial Vehicle with a Modified Fuzzy Controller in the Flight Control Loop, *Polyot*, 2013, no. 2, pp. 24–30. (In Russian.)
19. Ulianov, G.N., Ivanov, S.A., and Vladyko, A.G., The Model of Controlling the Unmanned Aerial Vehicle with a Fuzzy Logic Controller, *Information and Control Systems*, 2012, no. 4, pp. 70–73. (In Russian.)
20. Matveev, E.N. and Glinchikov, V.A., Fuzzy Logic Conclusion in the Control System UAV, *Journal of Siberian Federal University. Engineering & Technologies*, 2011, no. 4, pp. 79–91. (In Russian.)
21. Sarabakha, A. and Kayacan, E., Type-2 Fuzzy Logic Controllers Made Even Simpler: From Design to Deployment for UAVs, *IEEE Transactions on Industrial Electronics*, 2018, vol. 65, no. 6, pp. 5069–5077.
22. Mikhalev, I.A., Okoemov, B.N., and Chikulaev, M.S., *Sistemy avtomaticheskogo upravleniya samoletom* (Aircraft Automatic Control Systems), Moscow: Mashinostroenie, 1987. (In Russian.)
23. Besekerskii, V.A. and Popov, E.P., *Teoriya sistem avtomaticheskogo regulirovaniya* (Theory of Automatic Control Systems), 4th ed., St. Petersburg: Professiya, 2007. (In Russian.)
24. Ostoslavskii, I.V. and Strazheva, I.V., *Dinamika poleta. Traektorii letatel'nykh apparatov* (Flight Dynamics. Aircraft Trajectories), 2nd ed., Moscow: Mashinostroenie, 1969. (In Russian.)

This paper was recommended for publication
by L.B. Rapoport, a member of the Editorial Board.

Received December 21, 2021, and revised August 17, 2022.
Accepted September 27, 2022.

Author information

Pervushina, Natal'ya Aleksandrovna. Cand. Sci. (Phys.–Math.), Zababakhin All-Russian Research Institute of Technical Physics (VNIITF), Russian Federal Nuclear Center, Snezhinsk, Russia
✉ p-n-a100678@yandex.ru

Frolova, Antonina Dmitrievna. Research Engineer, Zababakhin All-Russian Research Institute of Technical Physics (VNIITF), Russian Federal Nuclear Center, Snezhinsk, Russia
✉ antonina.garishina@yandex.ru

Cite this paper

Pervushina, N.A. and Frolova, A.D., Designing an Adaptive Stabilizing System for an Unmanned Aerial Vehicle. *Control Sciences* **5,** 2–12 (2022). http://doi.org/10.25728/cs.2022.5.1

Translated into English by *Alexander Yu. Mazurov*,
Cand. Sci. (Phys.–Math.),
Trapeznikov Institute of Control Sciences,
Russian Academy of Sciences, Moscow, Russia
✉ alexander.mazurov08@gmail.com